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P. Coteus[(1)], M. Binkley[(3)], F. Bossi[(6)], J. Butler[(3)],
J. P. Cumalat[(1)], M. DiCorato[(5),(6)], M. Diesburg[(2)], J. Enagonio[(1)],
J. Filaseta[(2),(a)], P. L. Frabetti[(4)], I. Gaines[(3)], P. Garbincius[(3)],
M. Gormley[(3)], J. Haggerty[(3)(b)], D. J. Harding[(3)], T. Kroc[(2)],
R. Ladbury[(1)], P. Lebrun[(3)], P. F. Manfredi[(5),(6)], J. Peoples[(3)],
A. Sala[(6)], C. Shipbaugh[(2)], J. Slaughter[(3),(c)], J. Wiss[(2)]

[(1)]University of Colorado
Boulder, Colorado 80303

[(2)]University of Illinois at Urbana-Champaign
Urbana, Illinois 61801

[(3)]Fermi National Accelerator Laboratory
Batavia, Illinois 60510

[(4)]Universita di Bologna, Dipartimento di Fisica and I.N.F.N.
Bologna, Italy

[(5)]Universita di Milano, Dipartimento di Fisica
Milano, Italy

[(6)]Istituto Nazionale di Fisica Nucleare
Milano, Italy

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P. COTEUS[1], M. BINKLEY[3], F. BOSSI[6], J. BUTLER[3], J. P. CUMALAT[1], M. DICORATO[5],[6], M. DIESBURG[2], J. ENAGONIO[1], J. FILASETA[2],[a], P. L. FRABETTI[4], I. GAINES[3], P. GARBINCIUS[3], M. GORMLEY[3], J. HAGGERTY[3],[b], D. J. HARDING[3], T. KROC[2], R. LADBURY[1], P. LEBRUN[3], P. F. MANFREDI[5],[6], J. PEOPLES[3], A. SALA[6], C. SHIPBAUGH[2], J. SLAUGHTER[3],[c], J. WISS[2]

[1] *University of Colorado, Boulder, Colorado 80303*

[2] *University of Illinois at Urbana-Champaign, Urbana, Illinois 61801*

[3] *Fermilab, Batavia, Illinois 60510*

[4] *Universita di Bologna, Dipartimento di Fisica and I.N.F.N., Bologna, Italy*

[5] *Universita di Milano, Dipartimento di Fisica, Milano, Italy*

[6] *Istituto Nazionale di Fisica Nucleare, Milano, Italy*

ABSTRACT

We report on the observation of a narrow resonance at a mass of 2459 MeV/c^2 in the final states $\Lambda K^-\pi^+\pi^+$ and $\Sigma^0 K^-\pi^+\pi^+$. The mass, width, lifetime, and decay modes support the interpretation of a hadronically produced charm-strange baryon, the Ξ_c^+ . We present our measurements of the lifetime, cross section and relative branching fractions, and the A, x_f, and p_t dependence of the state.

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An observation of a long-lived, narrow state in the reaction (135 GeV) Σ^- + Be $\rightarrow \Lambda K^- \pi^+ \pi^+$ + X at a mass of 2460 $\pm$ 15 MeV/c^2 with quark content (csu) has been previously reported.[1] Our observation confirms the existence of the Ξ_c^+ , and its long lifetime. We also observe a second decay mode of the Ξ_c^+ and provide information on Ξ_c^+ formation from incident neutrons at considerably higher energy and in a new regime of x_f.

The experiment was performed at Fermi National Accelerator Laboratory. The beamline transported neutrons produced at 0° from the collision of 800 GeV/c incident momentum protons on a beryllium target. The neutron energy spectrum is triangular, with a most probable energy at approximately 600 GeV. The contribution to the neutral beam from gammas and K_l^0's above 200 GeV was negligible.

The detector, shown schematically in fig. 1, consists of an active target and vertex detector, a magnetic spectrometer, gas Cerenkov system, and electromagnetic and hadronic calorimetery. The neutrons impinged on three targets, in order upstream to downstream W, Si, and Be. The W and Be targets were respectively 300 μ and 4000 μ thick. The Si target was composed of ten 200 μ wafers (for a total thickness of 5000 μ with spacers), instrumented for charge readout. A fourth target, of three Si wafers, followed the Be. The targets, located in a common vacuum, were separated along the beam by 2.5 cm. Thus the primary interaction took place at a well defined point in z while long-lived charm decays occurred primarily in the space between targets. Immediately following the target region was a vertex detector consisting of 9 planes of MWPC's, with 250 μ wire spacing in three views.[2] The main magnetic spectrometer consisted of three stations of MWPC's between analyzing magnets M1 and M2 and two stations of MWPC's following M2. The angular acceptance for tracks through M1 was $100mr \times 200mr$, decreasing to $40mr \times 50mr$ for two magnet tracks. Each station of MWPC consisted of three views of wires with 2 mm spacing.The spectrometer has a measured resolution of $\sigma_p/p = .0002p$ for tracks traversing both magnets, and $\sigma_p/p = .0014p$ (p in GeV/c) for tracks traversing just one magnet. Approximately 7 GeV/c of momentum was required to traverse the entire detector while the minimum measured track momentum was approximately 1 GeV/c.

Charged particle identification was accomplished using three Cerenkov counters, operating (from upstream to downstream) with pion thresholds of 2.8, 10.8, and 5.7 GeV/c respectively. Each counter contained 34 separate cells. For tracks traversing all three detectors, protons could be uniquely identified from 20 to 80 Gev/c, while unique kaon identification extended from 10 to 40 GeV/c. Neutral kaons and lambdas were reconstructed if they decayed at least 15 cm downstream of the target and upstream of the center of M2.

The neutron energy was obtained by summing the output of the 3 calorimeters shown in fig. 1 . The summed response of the first two calorimeters (made respectively of leaded glass and steel-scintillator and containing a 3.8 cm radius beam hole) comprised our minimum energy trigger. A third calorimeter measured energy passing through the beam hole. The neutron flux of approximately 1.5×10^7 per 20 second pulse was low enough to reduce the energy contamination from multiple neutrons to a negligible level.

For this analysis we used a sample of approximately 45 million events. The primary interaction trigger was a coincidence between target region scintillation counter T1 and two coincidences in the downstream scintillator hodoscope HxV.

Ten percent of the data was recorded with this minimum bias requirement, while the rest of the data was accumulated with the additional requirements: a) A minimum neutron energy of 265 GeV. b) A minimum multiplicity of 4 charged tracks. c) A deposited charge in the most downstream active silicon target equivalent to 2 or more charged tracks. d) At least 1 charged kaon with momentum over 21 GeV/c traversing the entire detector.[3,4]

All triggers satisfying requirements a) through d) were processed through an analysis which found all charged tracks and a common vertex, then performed a Cerenkov counter analysis and searched for all K_s and Λ candidates. For the final state reported, all events containing a Λ within ± 14 MeV/c^2 of the nominal mass were further processed. All tracks were traced through the vertex detector. An acceptable fit to all chamber hits, including timing information (our MWPC's had recorded drift times), was required for a successful link. Approximately 10% of the main spectrometer tracks were unlinked with the vertex detector and did not reconstruct as part of a K_s or Λ decay. These unlinked tracks were not used in the Ξ_c^+ analysis.

Each track of the Λ was traced to the primary event vertex and its impact parameter (d) computed. If $d \leq 2$ mm (approximately 2 σ), the track was called attached to the primary vertex. Any Λ which contained two attached tracks, or which contained two links through the vertex detector was removed from the Λ category. Lambdas with one attached track were removed unless there was Cerenkov information supporting a proton (fastest track) hypothesis. Any Λ without positive proton identification, which when reconstructed as a $\pi^+\pi^-$ state fell within ± 18 MeV/c^2 of the K_s mass, was also removed from the Λ sample. Charged kaons were required to be uniquely identified as kaons, while pions were defined as any track which was not an electron, kaon, or proton. If no particle identification was possible, the pion hypothesis was assumed. Lastly, we formed Ξ_c^+ candidates by requiring the sign combination $\Lambda K^- \pi^+ \pi^+$, and requiring the Λ to have a larger momentum than either of the pions. In our Monte Carlo simulation of the production and (phase space) decay of the Ξ_c^+ , this last condition was satisfied for all geometrically accepted decays.

For each combination, all other tracks were used to form the primary vertex, using an algorithm which rejected tracks whose impact parameter at the vertex of all other tracks exceeded twice their resolution, which was about 60 μ (σ) for linked full spectrometer tracks. The measured resolution for minimum bias events with three or more charged tracks was approximately 1.0 mm (σ). To remove the effects of other long-lived decays in the event, the primary vertex was constrained in z to the center of the nearest target module. The $K\pi\pi$ of the Ξ_c were fit simultaneously to a vertex constrained to a line following the Ξ_c momentum vector and fixed at one end to the primary vertex. The free parameters were the $K\pi\pi$ track parameters and the z of the decay point. Candidates with unacceptable fits were removed from the analysis. To isolate events with relatively long lifetimes, the proper decay distance $z_p = (z(decay\ vertex) - z(primary\ vertex))\ /\ \gamma$ was computed. Except for error in the primary vertex, z_p would be momentum independent, since the decay vertex error scales with the decay candidate momentum. For low momentum (low $x_f = 2p_z^* \ / \ \sqrt{s}$) Ξ_c^+ candidates, the primary vertex error dominates the error of the decay vertex and z_p becomes an overestimate of the true significance of the secondary vertex detachment. Hence, with our target thickness and spectrometer acceptance, a large component of the background satisfying a minimum cut on z_p comes from non charm candidates with $x_f < .15$.

Figure 2 shows the mass spectrum for $\Lambda K^- \pi^+ \pi^+$ candidates with $x_f > .15$ after a successful constrained vertex fit, and the additional requirement that $z_p > .006$ cm . There are two narrow peaks above a smoothly varying background. We interpret this as two Cabibbo favored decays of the charm strange baryon, Ξ_c^+ : $\Xi_c^+ \to \Lambda K^- \pi^+ \pi^+$ and $\Xi_c^+ \to \Sigma^0 K^- \pi^+ \pi^+$; $\Sigma^0 \to \gamma \Lambda$. We have checked by Monte Carlo simulation that the effect of our detector resolution ($\sigma \sim 15$ MeV/c^2) is to make the width of the two $\Lambda K^- \pi^+ \pi^+$ states nearly identical. The separation in mass should be 75 MeV/c^2, corresponding to the energy of the missing gamma in the Ξ_c^+ center of mass frame. These expectations are confirmed by the superimposed fit of fig. 2 . The fitted function contains two independent gaussians and a second order polynomial background. A maximum likelihood fit yields a mass of 2459 $\pm$ 5 MeV/c^2 for the higher mass peak and a mass separation of 76 $\pm$ 8 MeV/c^2 between the peaks. We estimate a systematic uncertainty in the mass scale (checked by reconstruction of $K_s, \Lambda, \Xi^-, \Omega^-$, and D^0) of 30 MeV/c^2. The areas of the higher and lower mass peaks are respectively 55.7 $\pm$ 15.1 and 46.7 $\pm$ 15.7 events. The significance of the double peak system is 5.5 standard deviations. The widths of the two peaks are consistent with our resolution as determined by Monte Carlo. Our acceptance for the two decay modes is nearly identical, hence a ratio of the areas of the two peaks yields the branching ratio $B(\Xi_c^+ \to \Sigma^0 K^- \pi^+ \pi^+)$ / $B(\Xi_c^+ \to \Lambda K^- \pi^+ \pi^+) = .84 \pm .36$

To increase the data sample, we elected to determine the Ξ_c^+ lifetime without use of the x_f cut used in fig. 2. Data were grouped into five bins of z_p beginning at .012 cm (.40 ps). The bin sizes increase monotonically so that a Monte Carlo simulation with all detector resolution effects and with $\tau = .4$ ps has approximately equal number of events in the first four bins. All 5 bins were fit simultaneously to two gaussians and a polynomial background. When these event yields are compared to the Monte Carlo predictions as a function of τ, the two decay modes yield consistent values for the lifetime, further supporting our interpretation.The combined lifetime measurement for both decay modes is $.40^{+.18}_{-.12}$ ps where the errors are statistical only. As a test of systematic errors we made a second determination of lifetime by fitting the proper time (measured from our minimum time of .40 ps) of Ξ_c^+ candidates within $\pm$ 15 MeV/c^2 of the Ξ_c^+ mass to a pure exponential plus a time distribution for background events (determined from mass sidebands) appropriately normalized. With this method resolution effects are insignificant above a minimum time of .23 ps, which is also the proper time of background events. The average decay length (lab frame) of the background subtracted candidates is 10.2 mm. The resultant background subtracted lifetime distribution in the same 5 bins as above is shown in fig. 3. This method yields a combined lifetime of $.46^{+.17}_{-.12}$ ps. We quote the lifetime value from the first method with an additional systematic error of $\pm.10$ ps.

To determine the functional dependence of Ξ_c^+ production on x_f, p_t, and atomic number, we first require a minimum proper decay distance of .006 cm. We show in fig. 4 the efficiency corrected event yields as a function of x_f for both decay modes assuming a lifetime of .40 ps. The efficiency varies with x_f, from 1% at $x_f = .1$ to 0.1% at $x_f = .6$. Our efficiency drops quickly from $x_f = .1$ to $x_f = 0.$ due to geometric acceptance, while the efficiency change at large values of x_f reflects the momentum acceptance of the Cerenkov system and the finite Λ decay path. The efficiency variation with p_t is constant to within $\pm 7\%$ and can be safely integrated over, we find $dN \ / \ dx_f = (1 - x_f)^{4.7\pm2.3}$. For the same sample, requiring $x_f > .15$, integrating over the remaining x_f, and correcting for acceptance variation with p_t, we find a good fit to the form $dN \ / \ dp_t^2 = N_0 exp(-bp_t^2)$ with $b = 0.97 \pm .21(GeV/c)^{-2}$. The errors are statistical only. The neutron luminosity was determined from the number of minimum bias triggers, corrected for scintillation counter efficiencies and final state topologies (all neutral or 1 charged track) which would not fire the trigger. The product of cross section times branching fraction ($\sigma \cdot B$) for both decay modes is 7.5 μb per nucleon for the $0. < x_f < .6$ interval. The statistical error is 33%. We have ascribed a systematic error of 25%, to cover uncertainties in our corrections of acceptance and luminosity. We have also assumed an A dependence for charm production of $A^{\alpha=.90\pm.13}$, to be described. The error in α introduces yet another uncertainty in the charm cross section of +50% or -35%, where the correction is negative for a positive error in α. We add the two statistical errors in quadrature to obtain a total error of $^{+4.5+1.9}_{-3.6-1.9}$ μb.

For the event sample used in the p_t analysis we find $21 \pm 7, 49 \pm 13$, and 34 ± 11 decays in the W, Si, and Be targets. After correcting for the relative number of nuclei in the three target materials we find $\alpha = .90 \pm .13$ in the expression $\sigma(n + A_i \to \Xi_c^+ + X) \ / \ \sigma(n + A_j \to \Xi_c^+ + X) = (A_i \ / \ A_j)^\alpha$, where the errors are statistical only and we have averaged over $x_f > .15$. Our data suggests that Ξ_c^+ production has a stronger dependence on A than does the total inelastic neutron cross section, and is consistent with $A^{1.0}$ dependence.

In conclusion we have observed two narrow peaks in the final state $\Lambda K^- \pi^+ \pi^+$ with masses of 2382 GeV/c^2 and 2459 GeV/c^2, consistent with two different decay modes ($\Sigma^0 K^- \pi^+ \pi^+$ and $\Lambda K^- \pi^+ \pi^+$) of one long-lived state at $2459 \pm 5 \pm 30$ GeV/c^2 which we associate with the Ξ_c^+ . The ratio of branching fractions of these decay modes is $.84 \pm .36$. We determine a proper lifetime, τ, of $.40^{+.18+.12}_{-.10-.10}$

ps, and a $\sigma \cdot B$ of $7.5^{+4.5+1.9}_{-3.6-1.9}$ μb per nucleon for $0. < x_f < .6$. We find for the same range of x_f that $dN \;/\; dx_f$ fits $(1-x_f)^{4.7\pm 2.3}$, while $dN \;/\; dp_t^2$ fits $\exp(-bp_t^2)$ with $b = 0.97 \pm .21(GeV/c)^{-2}$. Lastly we find a cross section for the production from target nucleons varying as $A^{.90\pm .13}$.

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REFERENCES

a Present address: Northern Kentucky University, Highland Heights, KY 41076

b Present address: Brookhaven National Laboratory, Upton, NY 11973

c Permanent address: Yale University, New Haven, CT 06511

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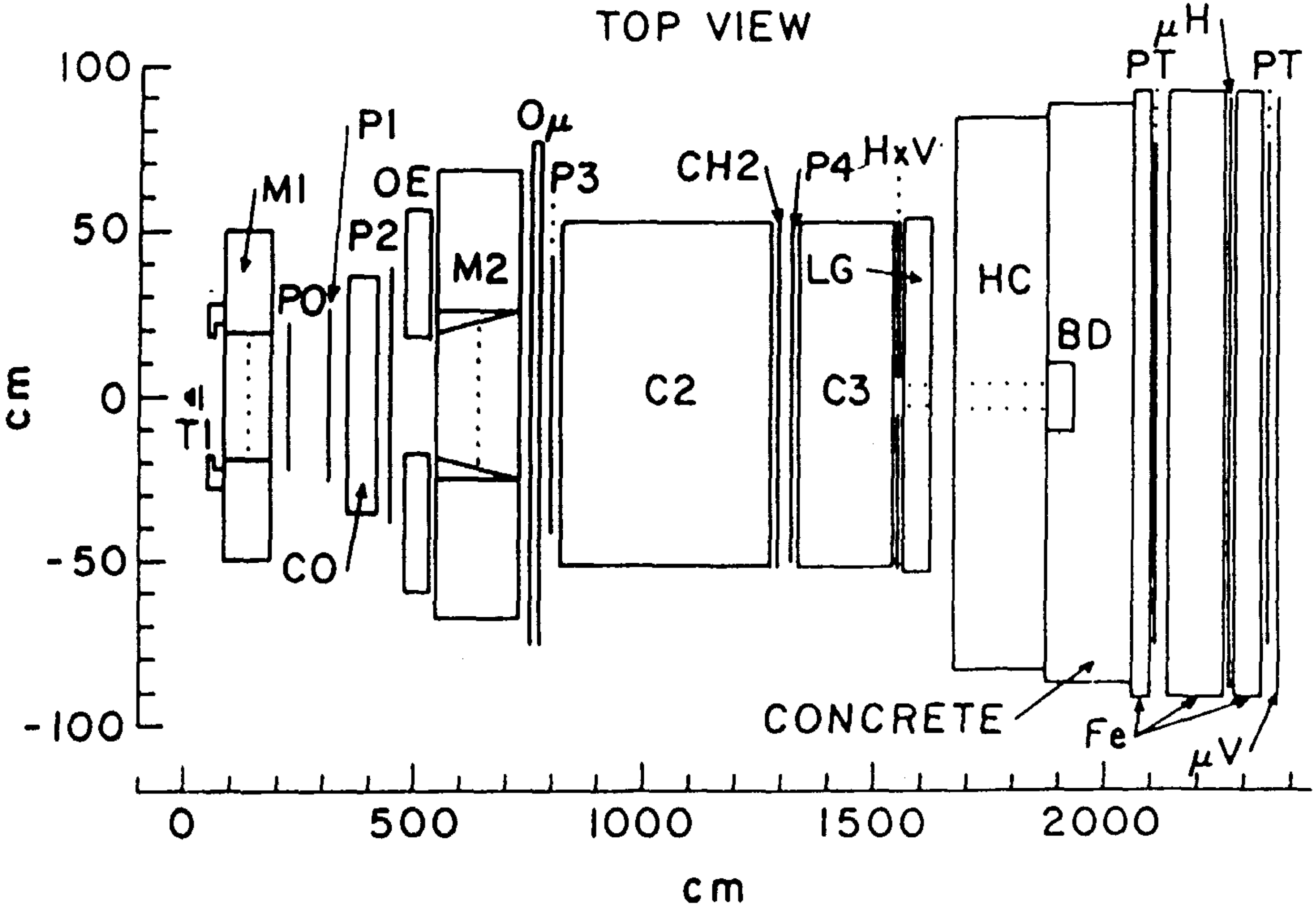
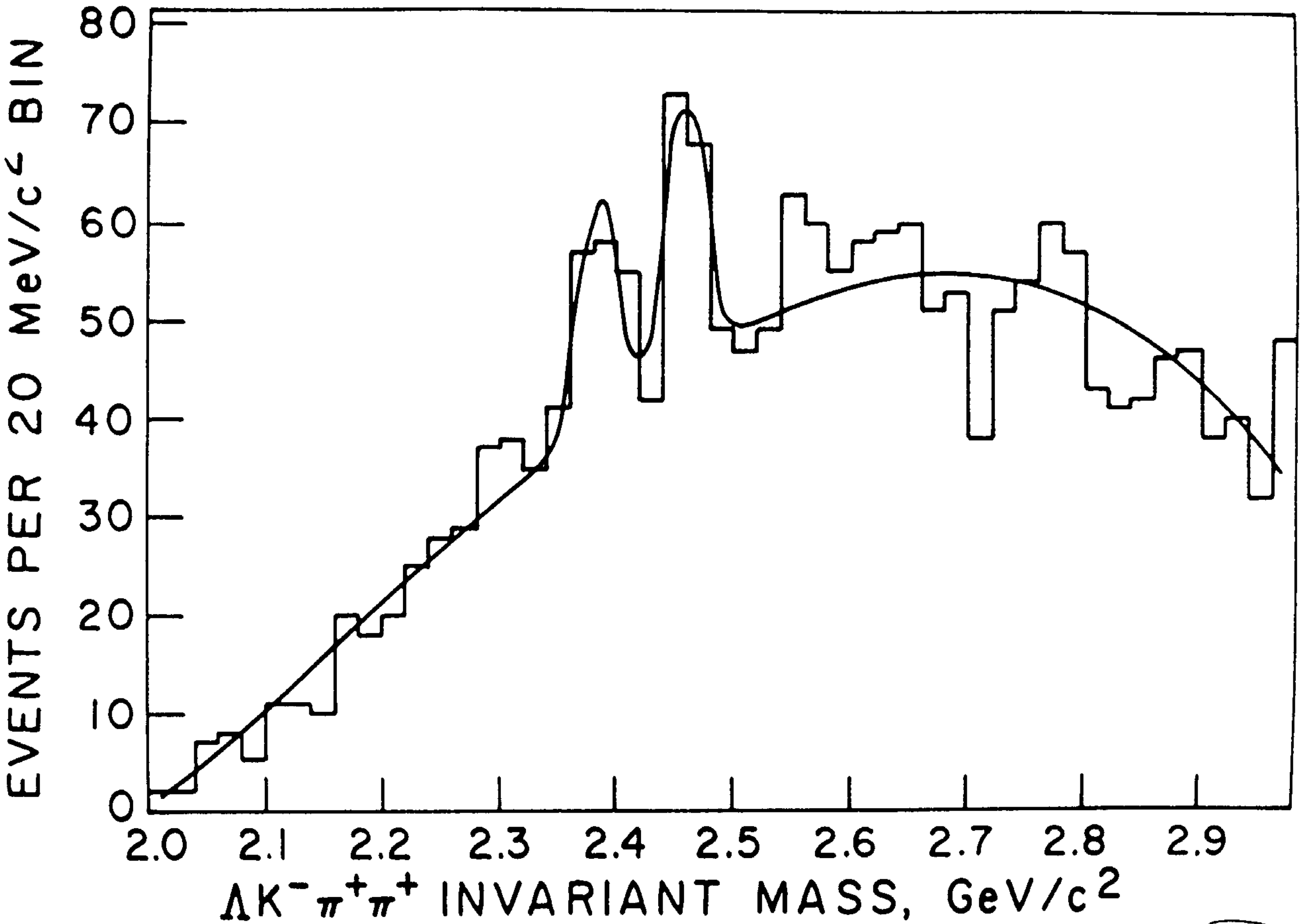
FIGURE CAPTIONS

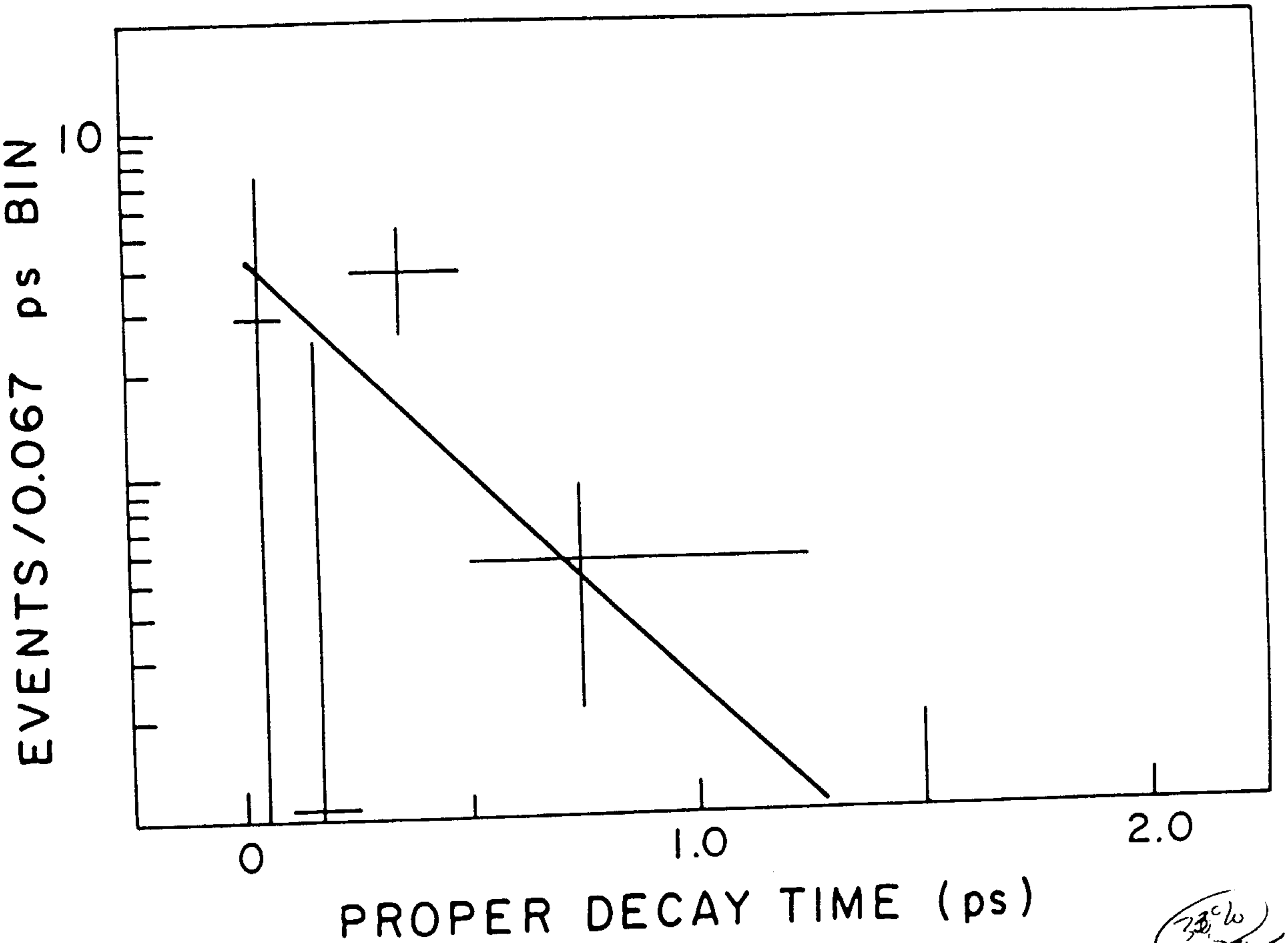
1. The E400 detector: P1-P4 are MWPC's; C0, C1, and C3 are Cerenkov counters; HC, BD, and LG are calorimeters; PT, μH, μV, and Oμ are muon detectors.
2. Mass spectrum of $\Lambda K^- \pi^+ \pi^+$ candidates
3. Proper time distribution of background subtracted Ξ_c^+ candidates
4. $dN \ / \ dx_f$ vs x_f

E-400, SPECTROMETER



12


EVENTS PER 20 MeV/c² BIN
0
10
20
30
40
50
60
70
80
2.0
2.1
2.2
2.3
2.4
2.5
2.6
2.7
2.8
2.9
ΛK⁻π⁺π⁺ INVARIANT MASS, GeV/c²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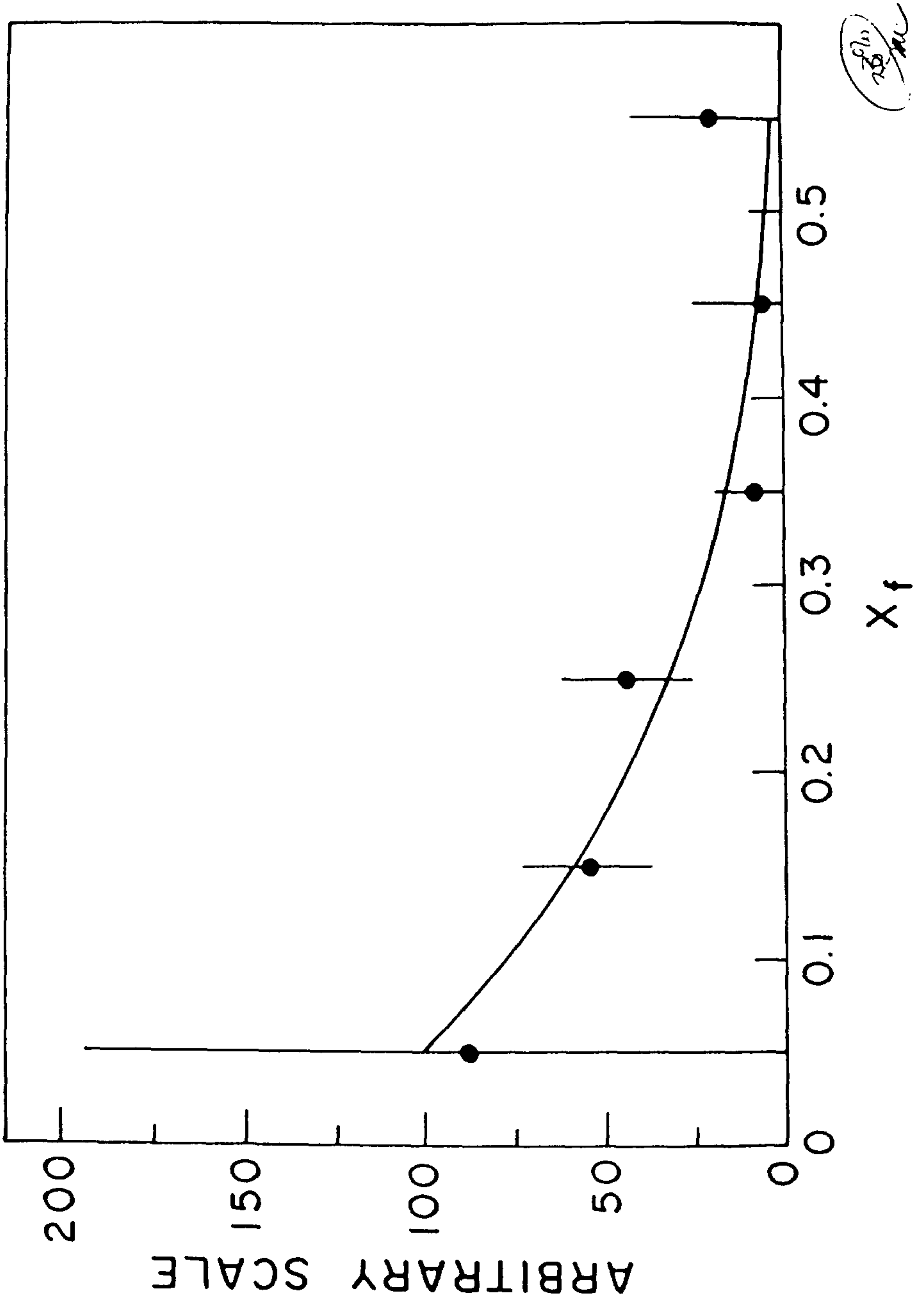
10
0
1.0
2.0
PROPER DECAY TIME (ps)


ARBITRARY SCALE
0
50
100
150
200
X_f
0
0.1
0.2
0.3
0.4
0.5